Novel Nano-Scale Conductive Films With Enhanced Electrical Performance and Reliability for High Performance Fine Pitch Interconnect

Yi Li, Myung Jin Yim, *Member, IEEE*, Kyoung Sik Moon, and C. P. Wong, *Fellow, IEEE*

***Abstract*—In this paper, a novel nano-scale conductive film which combines the advantages of both traditional anisotropic conductive adhesives/films (ACAs/ACFs) and nonconductive adhesives/films (NCAs/NCFs) is introduced for next generation high-performance ultra-fine pitch packaging applications. This novel interconnect film possesses the properties of electrical conduction along the z direction with relatively low bonding pressure (ACF-like) and the ultra-fine pitch $(< 30\ \mu\mathrm{m})$ capability (NCF-like). The nano-scale conductive film also allows a lower bonding pressure than NCF to achieve a much lower joint resistance (over two orders of magnitude lower than typical ACF joints) and higher current carrying capability. With low temperature sintering of nano-silver fillers, the joint resistance of the nano-scale conductive film was as low as 10^{-5} Ohm. The reliability of the nano-scale conductive film after high temperature and humidity test (85°C/85% RH) was also improved compared to the NCF joints. The insertion loss of nano-scale conductive film joints up to 10 GHz was almost the same as that of the standard ACF or NCF joints, suggesting that the nano-scale conductive film is suitable for reliable high-frequency adhesive joints in microelectronics packaging.**

***Index Terms*—Adhesives, contact resistance, , fine pitch capability, interconnects, sintering.**

I. Introduction

MICROELECTRONICS are driven toward smaller, higher density, and lower cost solutions. Polymer-based conductive adhesives have drawn much attention as an environmentally friendly solution for lead-free interconnects. Anisotropic conductive adhesives/films (ACAs/ACFs) are becoming popular as one of promising candidates for lead-free interconnection solutions due to their technical advantages such as fine pitch capability (<40-μm pitch), low-temperature processing ability, low cost, and environmentally friendly materials and process, etc. [1]–[6] ACAs/ACFs consist of conducting particles (typically 5–10 μm in diameter) and adhesives which provide both attachment and electrical interconnection between electrodes. In particular, ACFs are widely used for high-density interconnection between liquid-crystal display (LCD) panels and tape carrier packages (TCPs) to replace the traditional soldering or rubber connectors. In LCD applications, traditional soldering may not be as effective as ACFs in interconnecting materials between indium tin oxide (ITO) electrodes and TCP. Recently, ACFs have also been used as an alternative to soldering for interconnecting TCP input lead bonding to printed-circuit boards (PCBs). Also, NCAs/NCFs have been attractive due to the finer pitch capability and lowest cost options for interconnection materials without any conductive filler [7]–[12]. As the fine-pitch capability and low stress in the assembly is becoming hot issues, ACA/NCA interconnection materials can be used more frequently in joining materials.

However, there are several issues for ACF/NCF as lead-free interconnection application. Still they need high bonding pressure for the assembly and interconnection. ACF normally needs 100 gf per bump with bonding area of $100 \times 100\ \mu\mathrm{m}^2$ for reliable contact resistance. NCF typically needs more pressure than ACF such as 150–200 gf/bump, which is one of limits in the bonding process for their application [13]. Another limitation of ACF/NCF is the lower electrical properties compared to solder joints because there is only mechanical/physical contact of the joints and no metallurgical contact of interconnects. To ensure low-contact resistance and high-current density, interface between conductive fillers and electrode should be improved [14]–[16].

One of the approaches to minimize the joint resistance is to make the conductive fillers fuse each other and form metallurgical contacts such as metal solder joints. However, to fuse metal fillers in polymers does not appear feasible, since a typical organic PCB, on which the metal filled polymer is applied, cannot withstand the high melting temperature of conductive fillers. However, our previous studies demonstrated the low temperature sintering of nano-sized conductive fillers at the processing temperature of conductive adhesives [17]–[19]. As such, the use of the fine metal particles would be promising for fabricating adhesives with high electrical performance through eliminating the interface between metal fillers. The application of nano-sized particles can also increase the number of conductive fillers on each bond pad and result in more contact area between fillers and bond pads. Therefore, the use of nano-sized particles has potentials to improve the current density of the ACA joints by distributing current into more conductive paths.

In this paper, in order to resolve the technical issues (high bonding pressure and lower electrical performance) of traditional ACF/NCF while maintaining the advantages of ultra fine pitch and low cost, a novel nano-scale conductive film incorporated with very low loading of nano-Ag fillers were studied

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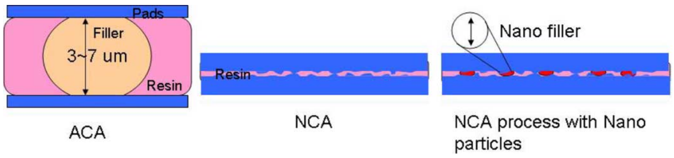


Fig. 1. Comparison of ACA, NCA, and novel NACF.

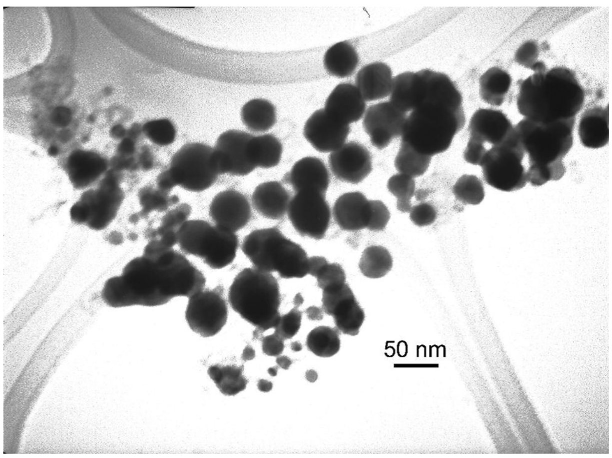


Fig. 2. TEM picture of the nano-silver fillers used in this study.

for next generation high performance fine-pitch packaging applications. This novel nano-Ag conductive film (as illustrated in Fig. 1) combines the electrical conduction along the z direction (ACF-like) and the ultra fine pitch (< 100 nm) capability (NCF-like). The morphology of nano fillers and ACF joints was characterized by using scanning electron microscopy (SEM). The effects of nano-filler incorporation and sintering on the electrical performance and reliability of novel adhesive joints were investigated by comparing the current-voltage (*I–V*) relationship of traditional ACF/NCFs and the novel nano-Ag conductive film (NACF).

II. Experimental

The base formulation of a conductive film was prepared with epoxy, curing agent and silane coupling agent. Nano silver particles (from nGimat Corporation, Atlanta, GA) synthesized by the combustion chemical vapor deposition (CCVD) were used as fillers and the TEM picture of the nano silver particles is shown in Fig. 2. The particles were mixed with the base formation using sonication for three hours. The film was prebonded on the substrate at 80 $^\circ$C for 5 s. After removal of a liner film, the substrate was aligned and the final bonding was conducted at 180 $^\circ$C with the application of different bonding pressures. The electrical resistance of the joints (contact area: $100 \times 100\ \mu\mathrm{m}^2$) on Au-finished test vehicle was measured by a four-point probe method, where the current carrying capability was determined as the current at which the voltage shows nonlinear behavior in the *I–V* or the resistance abruptly increases in the current-resistance (*I–R*) curve. The metal bond pad was a gold-plated polyimide film substrate. The applied currents were varied from 0.5–4.0 A by a power supply (HP model 6553A, HP Hewlett Packard, Palo Alto, CA) and the voltage of the interconnect joints was measured by a Keithley 2000 multimeter (Cleveland, OH). The reliability of joints was conducted under the environment of 85 $^\circ$C/85%RH (using an accelerated temperature and humidity chamber, Lunaire Environmental, model CEO932W-4) by measuring the joint resistance periodically during aging.

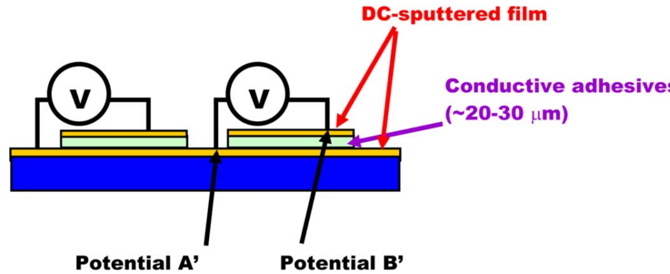


Fig. 3. Schematic illustration of dielectric property measurement of conductive adhesives.

To study the sintering behavior of nano-fillers, the nano Ag particles were annealed at different temperatures and the morphology of the annealed Ag particles was observed by scanning electron microscopy (SEM), (Hitach S-800).

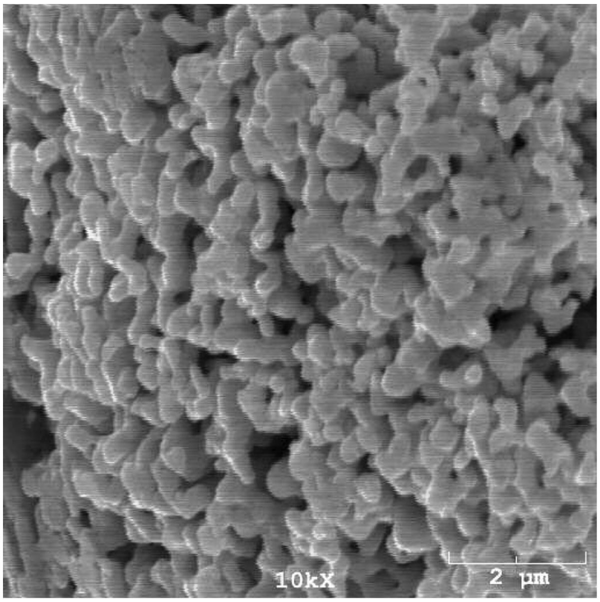
To characterize the insulation/dielectric properties, the conductive adhesives or films were coated on a Cu substrate (as a bottom electrode) with 20–30 $\mu\mathrm{m}$ thickness on which the top electrodes were created by a direct current (dc) sputter with a 3 mm diameter. Then two voltage probes were put on the top and bottom electrodes, respectively, as illustrated Fig. 3. Voltage was applied between top and bottom electrodes where the adhesive was located and a curve tracer was used to measure the breakdown voltages of the films.

The high-frequency measurements were conducted by using a vector network analyzer (VNA; HP Model 8720 ES) up to 10 GHz. For simple characterization and comparison among three adhesive materials, the *S* parameter S_{21} of flip chip joints using NACF, NCF, and micron-sized particle-filled ACF were measured. S_{21} indicates insertion loss of device under test (DUT). The test vehicle for the high-frequency electrical characterization consists of two-port GSG 500-$\mu\mathrm{m}$ transmission lines method used in the literature [20]. A 500-$\mu\mathrm{m}$ pitch GSG probe was used for the two-port measurements. For simple characterization and comparison among three adhesive materials, the *S* parameters were measured.

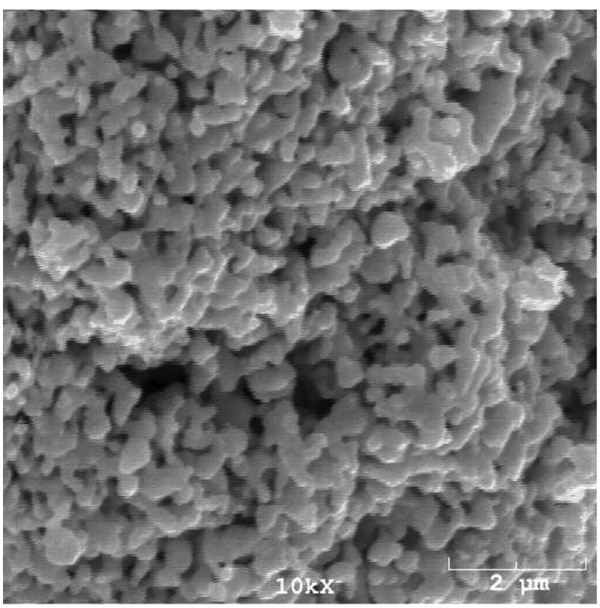
III. Results and Discussion

A. Sintering of Nano Ag Particles

In order to study the morphology and sintering behavior, the nano Ag particles were annealed at 180 $^\circ$C and 250 $^\circ$C for 30 min, respectively. From SEM photographs shown in Fig. 4, obvious sintering behavior has been observed after annealing. The particles were fused through their surface and many of dumbbell type particles could be found. The morphology was similar to a typical morphology of an initial stage in the typical sintering process of ceramic, metal, and polymer powders. This low temperature sintering behavior of the nano particles is attributed to the extremely high interdiffusivity of the nano



(a)



(b)

Fig. 4. SEM photographs of nano Ag particles annealed at (a) 180 °C and (b) 250 °C for 30 min.

particle surface atoms, due to the energetically unstable surface status of the nano particles, in particular, their high surface-to-volume ratios. However, there was not much difference in morphology for the particles annealed at 180 °C and 250 °C, indicating 180 °C (a typical curing temperature for ACA/NCA materials) is sufficient to get the particles sintered.

B. Effects of Bonding Pressure on the Electrical Property of NACF

In order to study the required bonding pressure to achieve low resistance, the bonding pressure during thermo-compression bonding of NACF and NCF joints was varied and the contact resistance was measured. Fig. 5 shows the relationship between the various bonding pressures (50–200 MPa) and the contact resistance of the joints.

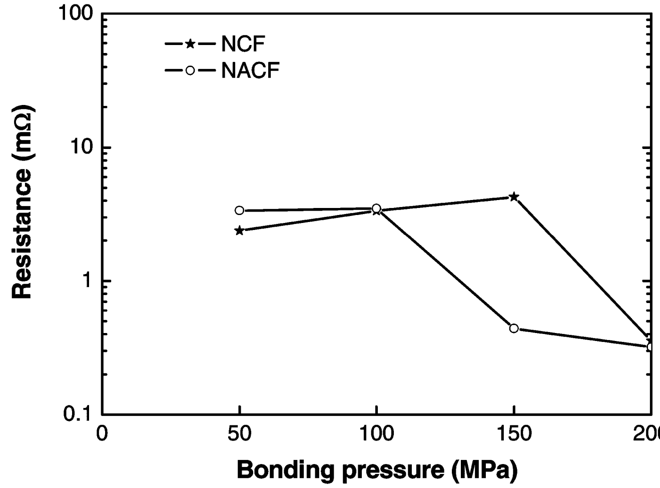


Fig. 5. Effects of bonding pressure on the joint resistance of NCF and NACF.

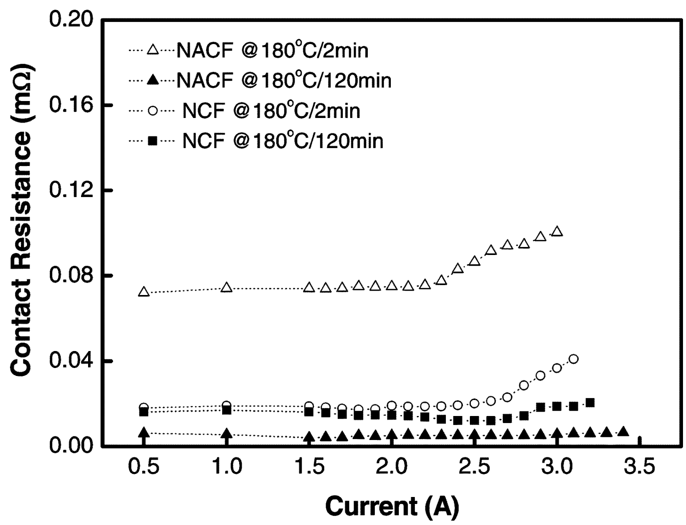


Fig. 6. *I–R* relationships of NACF and NCF joints with different curing time.

As the bonding pressure increases, the contact resistance of ACF/NCF joint generally decreases due to the contact area increment. For adhesives joints, there was a critical (minimum) pressure below which the contact resistance remained high. The result shows that the minimum bonding pressure for the NACF was 150 MPa, while the bonding pressure for NCF was 200 MPa. This implies that the required bonding pressure can be decreased for NACF joints.

C. Electrical Properties of NACF With Sintering

The *I–R* relationship of the NACF (1 wt% nano-Ag fillers) joints are shown in Fig. 6 with various curing conditions and compared with NCF joints. As can be seen from the figure, for the NACF joints cured at 180 °C for 2 min, a joint resistance of $\sim 0.08\ \mathrm{m\Omega}$ and current carrying capability of $\sim 2.4\ \mathrm{A}$ were observed. The joint resistance was two orders of magnitude lower than a typical ACF (0.6 $\mathrm{m\Omega}$ with micron-sized Au-coated polymer fillers as compared in Fig. 7), while the current carrying capability was similar. The reduced joint resistance for

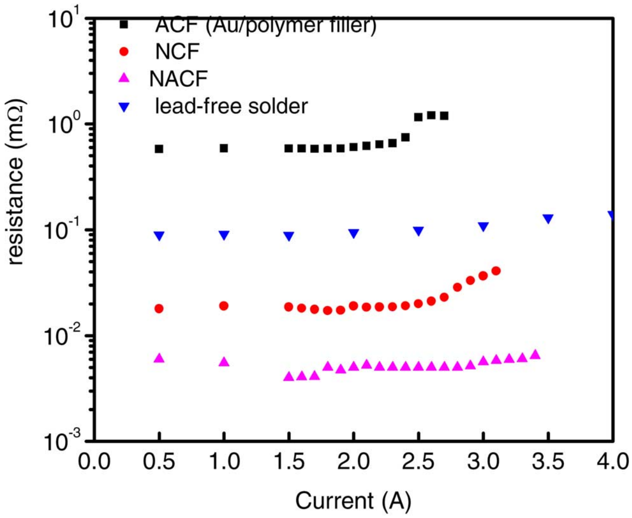


Fig. 7. Comparison of *I–R* relationships of typical ACF, NCF, and nano-Ag ACF.

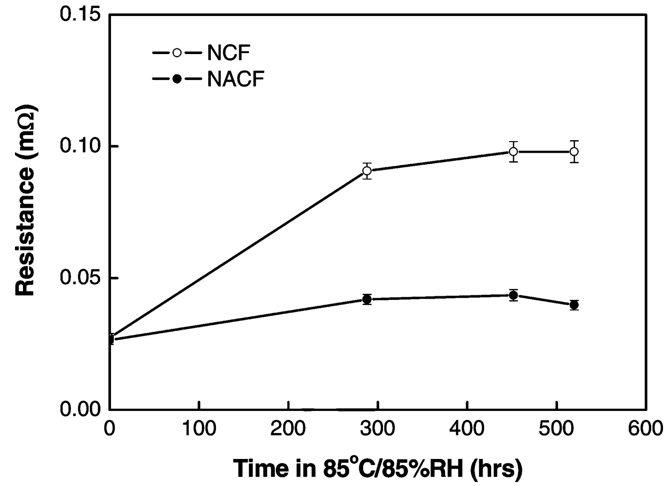


Fig. 8. Reliability of NCF and NACF under 85 °C/85%RH.

the NACF was attributed to the superior electrical conductivity of silver fillers. When increasing the curing time from 2 to 120 min the joint resistance was further reduced by over one order of magnitude (0.005 $\mathrm{m}\Omega$). In addition, the current carrying capability could also be enhanced from 2.4 to 3.4 A by prolonging the curing time. The further improved electrical performance (lower contact resistance and higher current density) is due to the further sintering with longer time. The more sintering of nano-sized fillers could enhance the interfacial properties of the joints. As such, the joint resistance, which is a sum of bulk resistance and interfacial resistance, would be significantly reduced. In addition, the thermal properties could also be enhanced by improving the interfacial properties. The higher thermal performance could help dissipate the heat more efficiently at the adhesive joints. Therefore, with further sintering of nano-Ag fillers, the current carrying capability was also improved. Although the NCF joint had much lower resistance than the NACF when they were cured at 180 °C for 2 min, prolonging the curing time to 120 min for the NCF joint did not induce much improvement of the joint resistance and current carrying capability.

The *I–R* relationship of NACF was compared with those of the NCF and a conventional ACF filled with micron-sized Au-coated polymer balls, as shown in Fig. 7. With the sufficient sintering, the joint resistance of the NACF was much lower than that of the conventional ACF. In addition, the current carrying capability was also dramatically enhanced due to the superior interfacial properties and the more efficient thermal transport. The joint resistance and current carrying capability were even better than those of the NCF and lead-free solder joints, due to the lower resistance of Ag fillers compared to the lead-free solders.

D. Reliability of NACF Joint

The electrical reliability of NACF joint was evaluated at the elevated temperature and humid environment (85 °C/85%RH). Fig. 8 shows the contact resistance behaviors of NACF and NCF joints under 85 °C/85%RH condition for over 500 h. The graph clearly shows that the NACF joint had more stable joint resistance than NCF joints with aging at 85°C/85%RH, indicating a better reliability. This reliability improvement should be attributed to the stable electrical contact between two Au electrodes by sintering effect of nano-Ag fillers even under the moisture absorption and hygrothermal expansion due to high temperature and humid test condition.

TABLE I
INSULATION PROPERTIES OF CONDUCTIVE FILMS

Sample name	Filler type	Breakdown voltage (V)
Typical ACF	Au/polymer (1wt%)	400 ~ 450
NACF-1	Nano-Ag (1wt%)	Short
NCF	No filler	1200 ~1400

TABLE II
COMPARISON OF INSULATION PROPERTIES OF NANO-SCALE ACF AND NCF

Sample name	Filler type	Breakdown voltage (V)
NACF-1	Nano-Ag (1wt%)	Short
NACF-2	Nano-Ag (0.1wt%)	1000-1400 V
NACF-3	Nano-Ag (with acid protection)	1000-1400 V
NCF	No filler	1200 V-1400 V

E. Insulation Properties of Nano-Scale Conductive Films

For NCF and/or ACF joints, not only a high electrical property in the z direction is important, but also the good insulation property in the x–y plane is required. Voltage was applied in between top and bottom electrodes where the adhesive was located and a curve tracer was used to measure the breakdown voltages of the films. As shown in Table I, the typical ACF with 1wt% micron-seized Au/polymer fillers showed a breakdown voltage of 400 V and the NCF joint had a much higher breakdown voltage. However, the NACF with 1wt% nano-Ag fillers showed a very

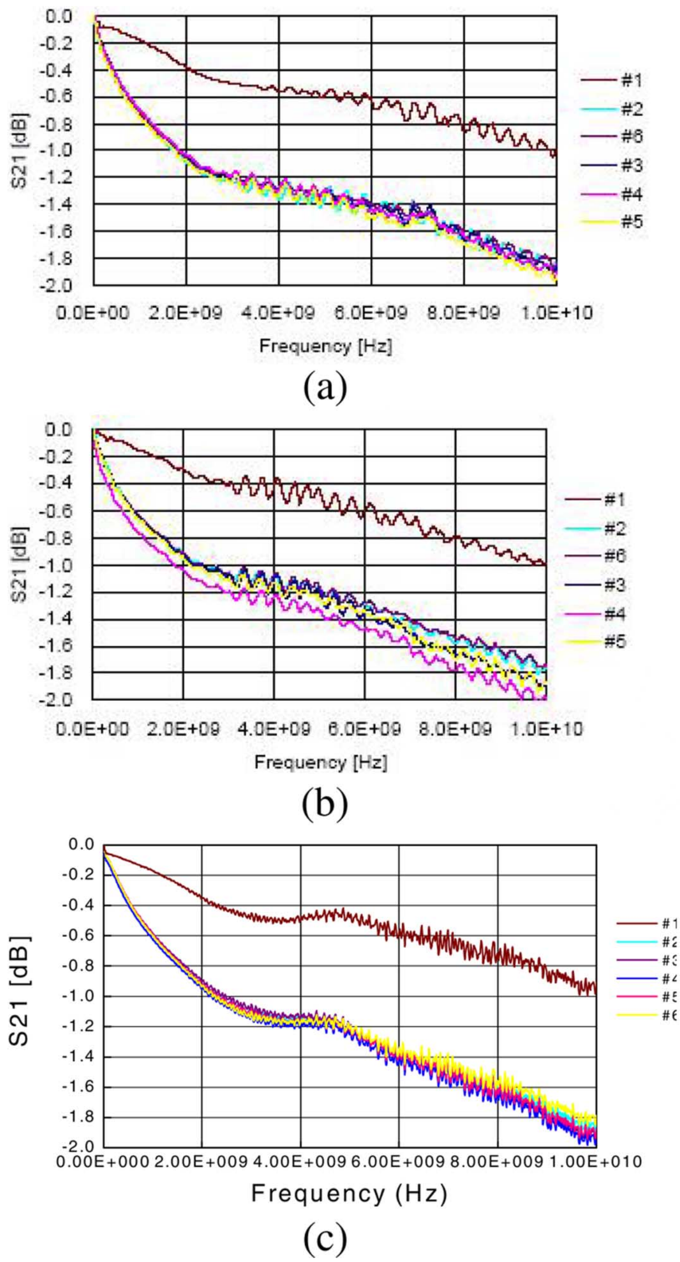


Fig. 9. VNA measurement results of (a) typical ACF joints with micro-sized fillers, (b) NCF joints, and (c) NACF joints.

low breakdown voltage, indicating the poor insulation property, probably due to the high conductivity of nano Ag fillers.

In order to improve the insulation property of the NACF, there are two possible approaches. One is to reduce the filler loading of conductive fillers. For the nano-sized fillers, the percolation threshold for conductivity would be much lower than the micron-sized fillers, mainly due to the high surface area of the nano conductive fillers. Therefore, low resistance can be achieved at a much lower filler loading. As shown in Table II, by lowering the filler loading from 1wt% to 0.1wt%, the breakdown voltage of the NACF can be significantly enhanced, indicating a good insulation property. Alternatively, the nano Ag fillers can be protected by organic monolayers which can mitigate the Ag bridging or the migration. It has been reported that carboxylic acids have strong affinity to Ag surfaces and tend to form the chelating compounds and protect the nano Ag fillers [21]–[23]. Therefore, difunctional carboxylic acid was used in the nano-Ag ACF formulations and the insulation properties were compared in Table II. Obviously, the monolayer protection of Ag nano-fillers was quite efficient in improving the insulation properties as well. The electrical properties of the low-filler loading and monolayer-protected NACF showed similar values as the typical nano-ACF with 1 wt% fillers. Therefore, the significantly improved insulation property of NACF was achieved without sacrificing the electrical performance.

F. High-Frequency Characteristics of NACF Joints

The high-frequency characteristic for the novel NACF joint is one of important properties for maintaining signal integrity in high speed flip-chip device interconnection. Therefore, it is necessary to characterize the high frequency behaviors of developed NACF in comparison with NCF and conventional micron-sized conductive filled ACF in the flip chip structure. Fig. 9 shows the high-frequency characteristics of ACF/NCF joints up to 10 GHz. The insertion loss of different ACF/NCF flip chip joints was almost the same, which indicated an acceptable high frequency behaviors of NACF compared with conventional ACF and NCF.

IV. CONCLUSION

In this study, a novel NACF which combines the advantages of both traditional ACAs/ACFs and NCAs/NCFs was introduced for next generation high performance fine-pitch packaging applications. This novel interconnect film combines the electrical conduction along the z direction with a relatively low bonding pressure (ACF-like) and the ultra fine pitch $(< 30\ \mu\mathrm{m})$ capability (NCF-like). With the low temperature sintering of nano-silver fillers, the joint resistance of the nano-scale conductive film could be as low as $10^{-5}\ \mathrm{Ohm}$, even lower than that of the NCF and lead-free solder joints. The reliability of the nano-scale conductive film was also improved compared to that of the NCF joints, while the insertion loss of nano-scale joints were almost the same as the standard ACF or NCF joints. Lowering the nano-Ag filler loading level or applying the monolayer protection on Ag particle surfaces could significantly improve the insulation/dielectric property of the x–y direction. The novel NACF in this study could be potentially used as high performance ultra-fine pitch lead-free interconnects in electronic packaging applications. However, particle size optimization, dispersion of nano-fillers in polymer matrix, voiding control by degassing or coupling agent, warpage control and particle entrapping need to be evaluated and resolved before the novel NACF can be implemented in the flip-chip packages.

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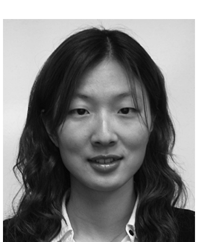

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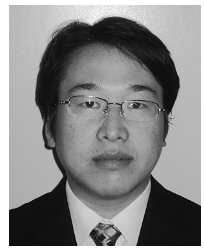
Her research interests focus on the materials and process on high-performance lead-free interconnect for electronics packaging, including the application of nano- and bio- materials in advanced polymer composites. Her research interests also include the thermal management of packaging. She is currently a Senior Packaging Engineer at Intel Corporation. She has published four book chapters, authored and coauthored 30 technical papers, and 40 conference proceedings.



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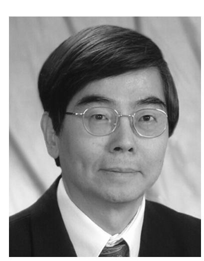

C. P. Wong (SM'87–F'92) received the B.S. degree from Purdue University, and the Ph.D. degree from Pennsylvania State University. After his doctoral study, he was awarded a two-year postdoctoral fellowship with Nobel Laureate Professor Henry Taube at Stanford University.

He is a Regents' Professor and the Charles Smithgall Institute Endowed Chair at the School of Materials Science and Engineering at Georgia Institute of Technology. He joined AT&T Bell Laboratories in 1977 and became a Senior Member of the Technical Staff in 1982, a Distinguished Member of the Technical Staff in 1987, and was elected an AT&T Bell Lab Fellow in 1992. Since 1996, he is a Professor at the School of Materials Science and Engineering at the Georgia Institute of Technology. He was named a Regents' Professor (highest rank professor) in July 2000, elected the Class of 1935 Distinguished Professor in 2004 for his outstanding and sustained contributions in research, teaching, and services, and named holder of the Georgia Tech Institute Endowed chair (one of the two institute chairs) in 2005. His research interests lie in the fields of polymeric materials,

materials reaction mechanism, IC encapsulation, in particular, hermetic equivalent plastic packaging, electronic manufacturing packaging processes, interfacial adhesions and nano functional material syntheses and characterizations. He holds over 50 U.S. patents, numerous international patents, and has published over 500 technical papers.

Dr. Wong received many awards, among those, the AT&T Bell Labs Fellow Award in 1992, the IEEE CPMT Society Outstanding and Best Paper Awards in 1990, 1991, 1994, 1996, 1998, 2002, the IEEE CPMT Society Outstanding Sustained Technical Contributions Award in 1995, the Georgia Tech Sigma Xi Faculty Best Research Paper Award in 1999, Best M.S., Ph.D., and undergraduate Theses Award in 2002 and 2004, respectively, the University Press (London) Award of Excellence, the IEEE Third Millennium Medal in 2000, the IEEE EAB Education Award in 2001, the IEEE CPMT Society Exceptional Technical Contributions Award in 2002, elected as holder of the Charles Smthgall Institute Endowed Chair at Georgia Tech in 2005, and the IEEE CPMT Field Award in 2006. He is a Fellow of the AIC and AT&T Bell Labs, and was the technical vice president (1990 and 1991), and the president of the IEEE-CPMT Society (1992 and 1993). He was elected a member of the National Academy of Engineering in 2000.